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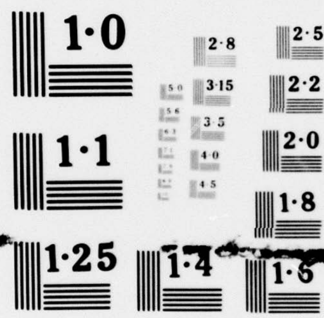
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SYSTEMS AND INFORMATION SCIENCES

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YALE UNIVERSITY
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SCATTERING OF UNDERWATER ACOUSTIC SIGNALS FROM A ROUGH, MOVING SURFACE

by

Franz B. Tuteur
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Henti Tung

Final Report Under Contract No. N00014-75-C-0298
S&IS Report No. 7705
June 1977

This work relates to Department of the Navy Contract N00014-75-C-0298 issued by the Office of Naval Research under Contract Authority NR 083-322. However, the content does not necessarily reflect the position or the policy of the Department of the Navy or the Government and no official endorsement should be inferred.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
CS-0298-1 ✓ (9) Final rept. 15 Nov 73-15 Nov 76,

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) Scattering of Underwater Acoustic Signals from a Rough Moving Surface.

5. TYPE OF REPORT & PERIOD COVERED
Final Report ✓
11/15/73 to 11/15/76

6. PERFORMING ORG. REPORT NUMBER
(14) CS-0298-1, S/IS-7705

7. AUTHOR(s)
(10) Franz B./Tuteur,
John G./Zornig
Henti/Tung

8. CONTRACT OR GRANT NUMBER(s)
(15) N00014-75-C-0298

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of Engineering & Applied Science ✓
Yale University
New Haven, Connecticut 06520

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
1761319.1461
NR083-322/9-30-74 480D

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research, Code 460
Department of the Navy
Bay St. Louis, Miss. 39520

12. REPORT DATE
(11) 1 June 1, 1977

13. NUMBER OF PAGES
(12) 22p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release-distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Underwater Acoustics, Propagation, Scattering, Doppler Side Bands, Wind Waves, Scattering Function, Interfrequency Correlation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(1) Calculation and Measurement of first and second-order moments of the channel transfer function;

(2) Spatial correlation between two receivers;

(3) Power scattered in directions other than forward; and

(4) Asymmetric Doppler amplitudes in forward scatter.

Each one of these projects is briefly discussed and summarized.

Abstract

This report covers work performed under Project NR083-322, Contract No. N00014-75-C-0298 during the three-year period starting November 15, 1973 and ending November 15, 1976. The research dealt with surface scattering and consisted of an experimental as well as a theoretical component. The experimental work was conducted in a model tank equipped with a wind tunnel to produce a wind-driven surface. The tank is very well instrumented and interfaced to a computer so that the experimental results can be accepted with considerable confidence.

Four separate projects are included in the work covered by this report. These are:

(1) Calculation and measurement of first and second-order moments of the channel transfer function

(2) Spatial correlation between two receivers

(3) Power scattered in directions other than forward

(4) Asymmetric Doppler amplitudes in forward scatter.

Each one of these projects is briefly discussed and summarized.

1. Introduction

This report contains a summary of research performed at Yale University under ONR project NR083-322 during the three-year period November 15, 1973 to November 15, 1976. Details are contained in a series of five technical reports CS1, CS3, CS6, CS7 and CS8, which have been submitted previously.

The research reported here was concerned mainly with various aspects of surface scatter of acoustic signals from the rough, wind-driven water surface. Both theoretical and experimental studies were carried out. During the early part of the contract period most of our work dealt with second-moment characterization of the surface scatter channel. More recently we have been concerned also with the calculation and measurement of asymmetric doppler side bands generated in surface scatter, and with the effect of multiple bounces both from the surface and from the bottom on the channel transfer function.

2. Surface Scattering Experiments

The experimental phase of the project was performed in a 24 ft. diameter model tank. The tank is equipped with a wind tunnel which produces a wind-driven surface of adjustable roughness. Acoustic signals are generated and received by piezo-electric transducers capable of handling signals in the frequency band of from 200 kHz to 1.3MHz. Surface wave heights are such as to produce Rayleigh parameters over a range of 10 to 0.1.

A major advantage of the model tank is that a very stable environment can be generated with it. This means that statistical measurements requiring many thousands of individual experiments under the same external conditions can be performed easily and routinely. Very high measurement precision can therefore be achieved. A data acquisition and processing system built around

a META-4 computer is an integral part of the experimental set up and contributes greatly to the ease and accuracy with which experiments can be performed. A detailed description of the facility as it existed at the beginning of the contract period is contained in report CS-1.

Since this report was written additional features have been added to the system. The most important of these is an automatic transducer positioning system that permits precise control of the azimunth, elevation, and aiming angle of the transducers. This system constitutes a goniometer of great accuracy and flexibility. A new wave-height measuring system has also been designed and constructed and is capable of very accurate measurements of surface statistics.

During the period of this project the following measurements were made

1. First and second-order moments of the channel transfer fuction
2. Spatial correlation between two receivers
3. Power scattered in directions other than forward
4. Asymmetric doppler amplitudes in forward scatter.

These four projects are briefly described below.

3.1 Channel Transfer Function--First-order Moment

It is assumed that the channel can be modelled as a linear, randomly time-varying transmittance. It can therefore be characterized by a transfer function $H(\omega,t)$, where the t dependence represents the random variation. For typical frequencies ω used in underwater communications, the variation in t is slow relative to $2\pi/\omega$. The first moment of the channel transfer function is

$$\phi_1(\omega) = \langle H(\omega,t)\rangle$$

where the symbol $\langle\ \rangle$ stands for statistical average. The function $\Phi_1(\omega)$

is sometimes referred to as the coherent transfer function and it measures the amount of spectral reflection from source to receiver.

Theoretical analyses of the scattering problem by Eckart [1] and others [2,3,4] indicate that $\phi_1(\omega)$ should match the shape of the characteristic function of surface displacement. Experimental measurement of this function generally corroborate this theoretical result for frequencies where the amplitude is no more than 20 db below its peak value. Beyond that point the experimental curve falls to a null followed by a peak rising substantially higher than the theoretically predicted value. In the neighborhood of the null the phase lag shows a rapid increase of between 90° and 180°.

While the unexpected null and peak occurred at very low amplitude levels they were associated with signal levels well above the background noise. The phenomenon is therefore significant. No fully satisfactory explanation for it has been found to date. Several plausible causes (beam pattern effects, multipath, quantization error) were effectively eliminated. Breakdown of the Kirchhoff assumption of geometric optics, which is basic to the theoretical treatment remains a possibility, although efforts to confirm this by appropriate parameter variations led to generally negative results. It should be noted that agreement to the point where the coherent transfer function falls more than 20 db below its peak value may well be sufficient to validate the theory for most practical purposes. For further detail, see report No. CS-1.

3.2 The Second Moment of the Channel Transfer Function.

The second moment of the transfer function is defined by

$$\phi_2(\omega,\omega',\mu) = \langle H(\omega,t)H^*(\omega',t+\mu)\rangle$$

where the asterisk denotes complex conjugation. The general form for this

function has been calculated using the Fresnel-corrected Kirchhoff integral method. Some of the details of this calculation are given in report No. CS-3 and in Refs. [2,5,6,7]. Briefly the calculation is based on the Kirchhoff approximation, the assumption of a gaussian surface, and the neglect of shadowing and of multiple reflections. A comparison between measured values of $\phi_2(\omega,\omega',0)$ and calculated values is given in report No. CS-1, Figs. 5.1 to 5.7, in report No. CS-6, Figs. 4,5,6 and 7, and in ref. [8] Figs. 4,5,6 and 7. In general the agreement between theoretical prediction and experiment has been excellent.

3.3 The Scattering Function

Both theory and experiment show that $\phi_2(\omega,\omega',\mu)$ is narrow-band in the sense that it has significant values only near the $\omega = \omega'$ axis. This suggests a change of variable $\omega = \omega_0$, $\omega' = \omega_0 + \Omega$, where $\Omega << \omega_0$. The resulting function can then be doubly Fourier transformed to yield the scattering function or range-doppler plot

$$S_{DR}(\tau,\nu;\omega_0) = \iint \phi_2(\omega_0,\omega_0 + \Omega,\mu)e^{j(\Omega\tau-\mu\nu)}d\mu d\Omega/2\pi$$

This function displays the time delay τ and doppler shift ν directly [9]. It has been investigated theoretically in several papers [5,6,7] that have resulted from this project, as well as in report No. CS-3. For sea surfaces having a dominant direction of wave motion $S_{DR}(\tau,\nu;\omega_0)$ has apparently the shape of a hollow horseshoe as is shown, for instance, in Figs. 2,4 and 5 of ref. [7], or in Figs. 3 and 7 of report No. CS-3. The hollow-horseshoe shape suggests strong correlation between delay and doppler in the sense that larger reverberation delays are associated with larger doppler shifts. This form of the scattering function suggests that communications signals

employing the surface-scatter channel might well be designed to match this characteristic, and thereby to substantially increase the data rate. An investigation of the feasibility of such signal designs is currently underway.

As of this writing the scattering function has not yet been experimentally determined in our tank. Experiments that have been performed in the ocean [10] do not reveal any horseshoe-shape; however this may be in part due to the fact that the ocean parameters are different from those assumed for the theory. We are planning experiments during the coming year that will indicate the form of scattering functions that can be obtained in the controlled environment of our test facility.

3.4 Multiple Bounces

One of the factors that may contribute to the difference between the form of the scattering function measured in ocean experiments and as predicted from our theoretical model is that in most ocean experiments, in particular the ones described in ref. [10], there are no single surface-bounce paths. We have therefore begun an investigation of multiple bounces and their effect on the scattering function. Preliminary results are contained in report No. CS-8 as well as in refs. [11] and [12]. In the last one of these papers we show that multiple bounces may indeed largely eliminate the horseshoe effect. A complete analysis of the problem is currently being generated, and we hope to publish the results in the next few months.

3.5 Spatial Correlation

The second-moment that characterizes spatial correlation is

$$\phi_{12}(\omega,\omega',\mu) = \langle H_1(\omega,t)H_2^*(\omega',t+\mu)\rangle$$

where the subscripts 1 and 2 are used to designate two different transfer functions for signals from the source to two different receivers. The general form of this function has also been calculated using the Fresnel-corrected Kirchhoff integral method. The details of this computation are contained in report No. CS-6 and in ref. [8]. The function $\phi_{12}(\omega,\omega',0)$ (i.e. spatial separation, but no time shift between the two signals) has also been measured in our experimental facility. A comparison between theoretical and experimental results is contained in report No. CS-6 and ref. [8], and the agreement is generally excellent.

4. Back Scatter and Side Scatter

Measurement and calculation of surface scatter power in directions other than the forward direction has been one of the major activities of our group during the last few years. Only a small part of this effort was supported under the present contract; most of it was supported under Contract N0014-75-C-1014. A theoretical analysis of the problem is contained in the final report issued under this contract, dated June 1976. Additional results are contained in technical report No. CS-9 by P.M. Schultheiss, J.G. Zornig and J. Snyder to be issued shortly.

The theoretical analysis is based on the Fresnel-corrected form of the Kirchhoff integral and utilizes the usual assumptions associated with this formulation. A simple result of this analysis is that under the

the assumption of a gaussian surface with a simple surface correlation function the ratio of back scattered power to forward scattered power is given by

$$\frac{\text{Back scatter power}}{\text{Forward scatter power}} = \exp\left[-\frac{\cot^2\psi}{2S_{xx}^2}\right]$$

where ψ is the nominal grazing angle and S_{xx} is the r.m.s. surface slope. For a grazing angle of 15° and an rms surface slope of 15° (a rather rough surface) this equation yields a back scatter loss of the order of 600 db. Experimental measurements in the model tank show back scatter losses of between 35 and 50 db, depending on wind direction. This wide discrepancy between theory and experiment clearly shows that the underlying model leading to the simple formula given above is unrealistic. Similar wide discrepancies are found in scatter in other directions except forward, where theory and experiment coincide closely.

Alternative models for the surface have been considered. These are (a) composite surfaces, (b) nondifferentiable surfaces, and (c) non-gaussian surfaces. Each of these is briefly discussed below:

(a) Composite Surfaces. It is argued that the surface deformation consists of several superimposed wave trains with different amplitudes and spatial spectra. The surface is otherwise regarded as being Gaussian in two dimensions. It is assumed that the various components are statistically independent. Then

$$S_{xx}^2 = \sum_{i=1}^{n} S_{xx_i}^2$$

where S_{xx_i} is the mean-square slope of the i^{th} component. Since all the components are subject to the same hydrodynamic laws S_{xx}^2 may be considerably larger for a composite surface than it would be for a surface composed of a single wave component. However, since values of S_{xx_i} in excess of .05

(12° rms slope) are very unlikely an unreasonably large value of n would be required to generate back-to-forward scatter ratios of the magnitudes observed. An advantage of this model is that it can be experimentally tested. A probe system having the necessary resolution has been constructed but no results have as yet been obtained.

(b) Nondifferentiable surfaces

If one assumes that the surface correlation function has the form $\exp\{-a|\xi|\}$ the predicted back scatter is much higher than if the more commonly used forms $\exp[-a^2\xi^2]$ or $\exp[-a^2\xi^2]\cos\rho\xi$ are used. This approach was used successfully by Beckmann in order to obtain a good match to experimentally obtained back scatter from the lunar surface. The model is not, however, very convincing for sea surfaces, since the cusp in the correlation function at $\xi = 0$ implies that the surface is almost nowhere differentiable. This makes little sense from hydrodynamic grounds and has not been observed in practice.

(c) Nongaussian surfaces

A calculation has been performed in which the ratio of back-to-forward scattter is related to the probability density of the surface slope. The essential result is given by

$$\frac{\text{Back scatter power}}{\text{Forward scatter power}} = \frac{f_{sx}(\cot\psi)}{f_{sx}(0)}$$

where $f_{sx}(\cdot)$ is the probability density of slopes perpendicular to the direction of the acoustic signal and ψ is the grazing angle. The argument $\cot\psi$ can be

can be interpreted as the slope of a facet on the water surface which reflects energy back to the transmitter. Thus this expression relates the magnitude of back scattered power to the fraction of all surface facets that are oriented properly for backward reflection. For small grazing angles $\cot\psi$ is quite large (on the order of 4); hence the magnitude of the back scatter depends on the tail of the slope distribution at a point many standard deviations away from the mean. The unreasonably small value for the theoretically predicted back scatter level can then be related to the fact that the tail of the Gaussian distribution is extremely low. This suggests that deviations from Gaussian behavior far out on the tail of the slope distribution (where no good data are currently available) might be critical in predicted back scatter.

5. Asymmetric Sidebands

When a sinusoidal acoustic signal is scattered from a moving rough surface the received signal generally shows some frequency spreading. If the surface roughness is small and if the surface deformation is roughly periodic, the spreading consists of a fairly distinct sequence of side band frequencies. This is the result of phase modulation of the transmitted sinusoid, and the separation between the spectral lines at the receiver is equal to the surface frequency. If the surface is rough and confused the side bands merge together into a more or less continuous spreading of frequencies around the transmitted frequencies.

In several recent papers [13,14] E.Y. Harper and F.M. Labianca showed that if the transmitter and receiver are at different depths the upper and lower side bands may have different amplitudes. The amplitude ratio depends on the direction of the surface motion with respect to the transmitter-receiver geometry. Specifically, if the transmitter is at a greater depth

than the receiver and if the wind causes surface waves to travel from the transmitter toward the receiver, then the upper side-band amplitudes are smaller.

Report No. CS-7 contains an analysis of this problem based on the Fresnel-corrected Kirchhoff formulation. This report was mainly a feasibility study and should not be taken as a definitive analysis. It showed that asymmetric side-band amplitudes can be obtained by means of the Kirchhoff integral method if the usual specular-point expansion is replaced by an expansion designed to minimize the third-order term.

Measurements of the side-band spectra are quite simple in the experimental tank, and a number of such measurements have been performed. Some of the results of these measurements are shown in Figures 1 through 3. These measurements were all taken with a fairly rough surface so that instead of individual side-bands one would expect a continuous spread of frequencies. Fig. 1 shows the results for a symmetric source-receiver geometry in an upwind configuration, and, as expected, the resulting spectrum is essentially symmetric about the transmitted frequency. Results for an asymmetric source-receiver geometry are shown in Fig. 2. In this figure the spectrum is clearly asymmetric; for instance, the spectral level for 8 Hz above the transmitted frequency is about 1/2 as large as the level for 8 Hz below the transmitted frequency.

Unfortunately (or interestingly, depending on one's point of view), the observed asymmetry is just the reverse of that predicted by the theory. If the transmitter is at a greater depth than the receiver, and the wind direction is towards the receiver, the theory predicts the upper side band to be larger. Yet Fig. 2 (and other measurements that we have not shown)

indicate that the upper side band is smaller.

We believe that the reason for this discrepancy between theory and experiment can be traced to the effects of the narrow-beam pattern which is necessarily used (i.e. to get reasonable signal-to-noise ratios and to clearly define the scattered ray) in the experiment, but which is not included in the theory. Preliminary attempts have been made to adapt the theory to include narrow beam patterns, but this work has not been completed. Qualitatively it seems clear that beam pattern effects can be made to account for the observed asymmetry.

One of the most interesting measurement results is shown in Fig. 3. This shows a spectrum measured for a transmitter and receiver at the same depth with the wind at right angles to the acoustic signal path. The theory of Harper and Labianca, as well as that of report CS-7 would consider this as a symmetric geometry and would therefore predict a symmetric output spectrum. Instead we find a much more asymmetric spectrum than in Fig. 2. Considerable effort has gone into the development of a theoretical explanation of this observation. We assume that the source of the asymmetry can be found in the fact that the upwind slope of the surface is generally smaller than the down wind slope. A simple deterministic surface model using a Fourier decomposition of the surface of the form

$$z = a_1 \cos \omega x + a_2 \cos(2\omega x + \phi)$$

has been investigated. The appropriate sawtooth surface profile can be produced with this model by proper choice of a_1, a_2 and ϕ. In particular as ϕ is changed from zero to about $\pi/4$ the surface changes from a symmetric to a highly asymmetric form, and it is relatively easy to show that the spectral asymmetry varies in the same way. More recently we have also

considered random surfaces. By proper expansion of the normal derivative in the Kirchhoff integral we have been able to show that the observed spectral asymmetry can be traced to third-order moments of the surface. This model is consistent with the deterministic surface model already referred to insofar as the asymmetric terms introduced by the third-order moments disappear when the phase angle ϕ which controls surface asymmetry in the deterministic model is set to zero.

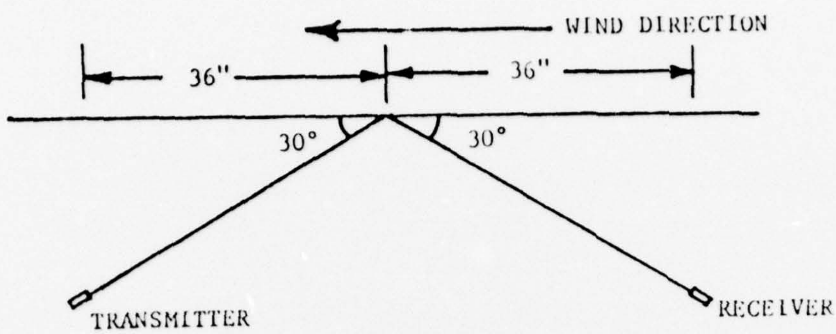
A report detailing these new developments is currently being written. When completed it will be issued as report No. CS-10, and it will be included as part of the work under the new ONR project No. NR-083-322 (Contract No. N00014-77-C-0237) which started in February 1977.

List of Figures

1. Experimental spectrum observed with source and receiver at the same depth in an upwind configuration.

2. Experimental spectrum observed with source depth twice as large as receiver depth, upwind configuration.

3. Experimental spectrum observed with source and receiver at the same depth, cross-wind configuration.



Wind = #4 $\gamma\omega_o \approx 5.0$

$\omega_o/2\pi$ = 0.5 MHZ 100 Files

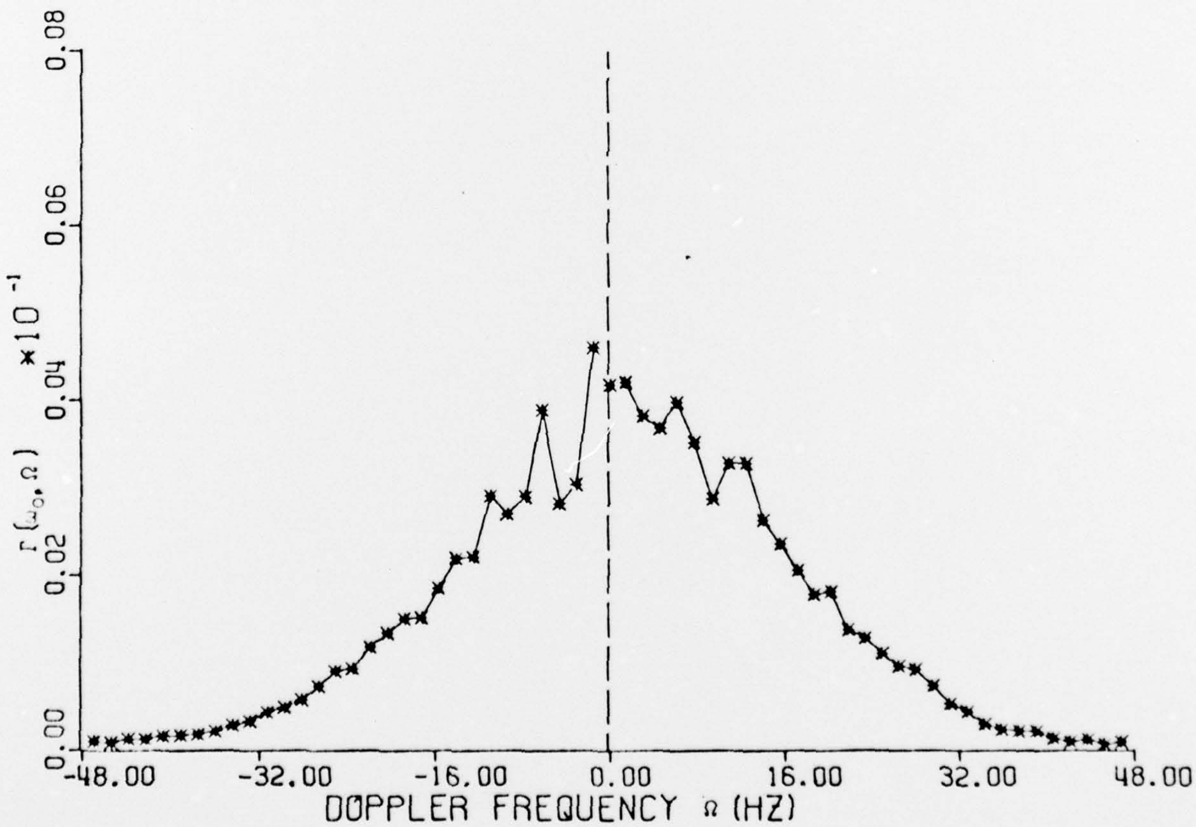
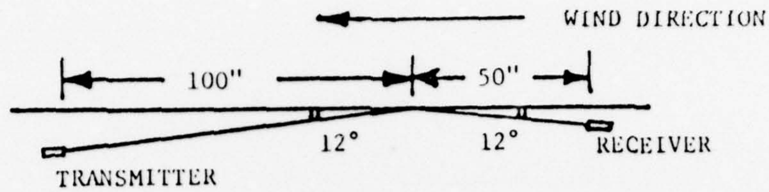


Figure 1



Wind = #4

$\gamma\omega_o$ = 2.5

$\omega_o/2\pi$ = 0.6 MHZ

95 Files

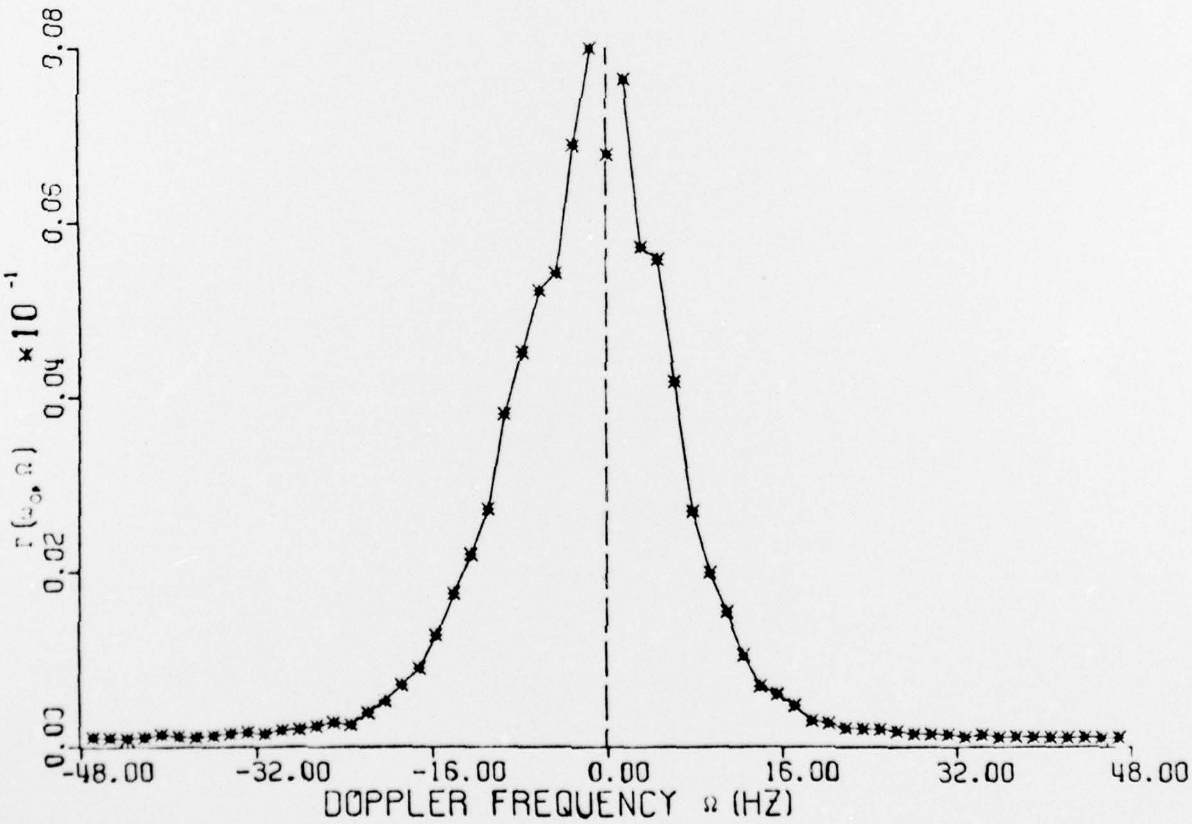
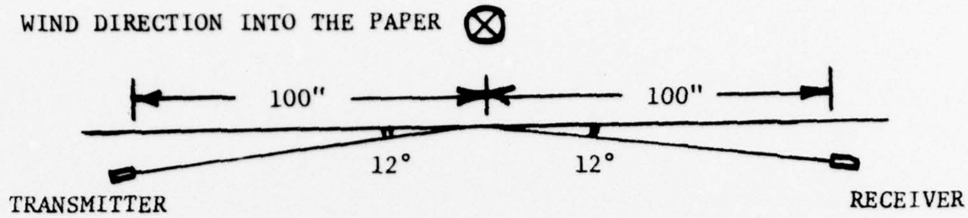


Figure 2



Wind = #4

$\omega_o/2\pi$ = 0.6 MHZ

$\gamma\omega_o \simeq 2.5$

100 Files

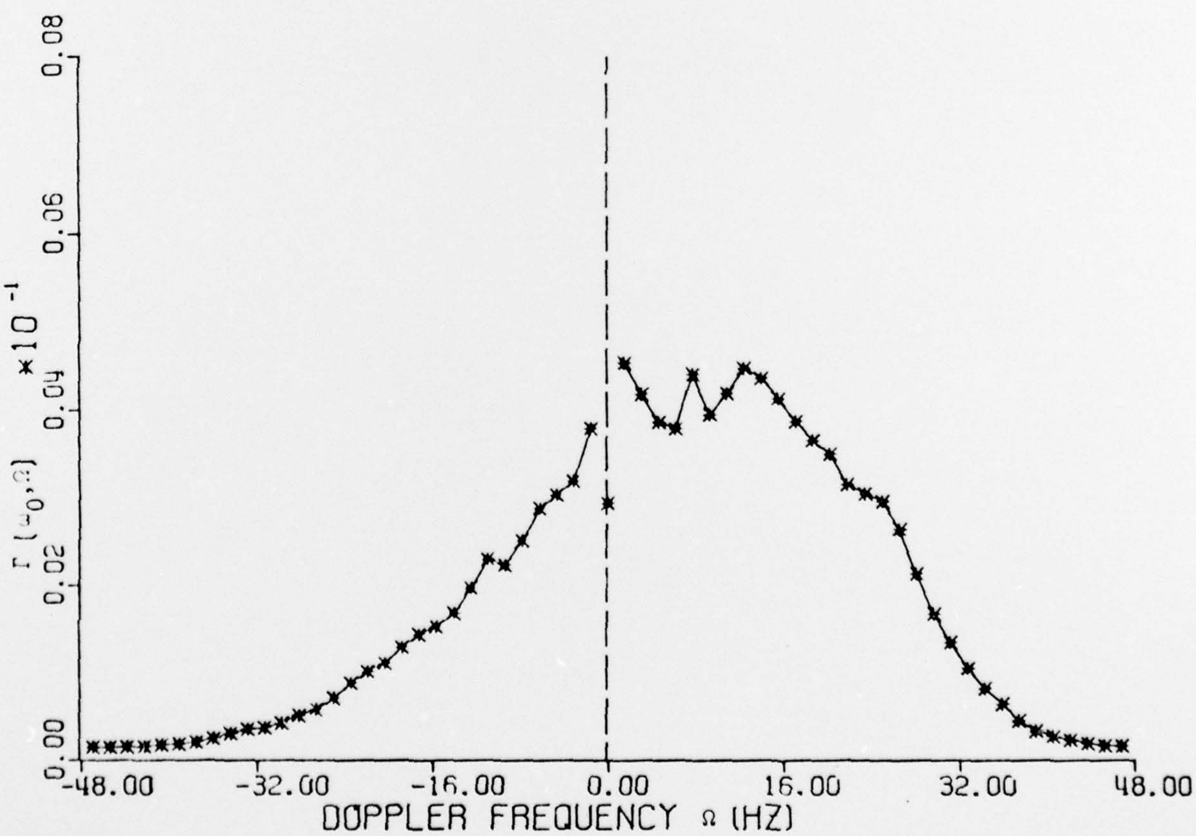


Figure 3

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